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Ringkøbing Fjord – Ecosystem functionality. Technical note.

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Conclusions

Ringkøbing Fjord, a 300 km² lagoon on the west coast of Jutland, is connected to the North Sea by a sluice at Hvide Sande. In 1995, it was decided to obtain a higher salinity. With this decision, the clam Mya Arenaria invaded the lagoon in large numbers with high filtration rates and effectively controlled the algae biomass and therefore also increased the secchi depth from 0.5 m to around 2 m. Due to this "top-down control" of the system, eutrophication is expressed by biomasses of Ulva and epiphytes, and there is generally no correlation between nitrogen loadings and chlorophyll. In the years around 2002-2014, a correlation between N-loading and Chlorophyll can be established properly due to a decrease in filtration from the clam Mya Arenaria. In the period 2008-2019 and 1998-2019, no correlations between N-loadings and chlorophyll can be established. Chlorophyll concentrations from 2010 to 2023 are on average 7.7 µg/l and below the target in the River Basin Management Plan 2021-2027 (8.4 µg/l) when excluding the 2 years (2019/2020) with poor filtration from Mya Arenaria. Secchi depth is correlated to chlorophyll and wind due to resuspension and hence no correlation between nutrients and secchi depth in the current system with "top-down control" from Mya Arenaria. The current vegetation depth limit and secchi depth suggest a maximum vegetation depth limit of 2.5 m and therefore below the target of 3.1 m in the River Basin Management Plan 2021-2027. Data suggest that a secchi depth of 3.1 m requires a summer chlorophyll-a concentration of 4.2 µg/l and therefore it does not seem likely that the chlorophyll (status and target) will support a 3.1 m vegetation depth limit goal in short to medium term. To support the clam Mya Arenaria in the lagoon for optimized filtration the average salinity in spring from Marts to May should be at least 8 psu (reference: surface 1 m, station close to Ringkøbing), and the average summer salinity from June to August should be at least 12 psu (reference: surface 1 m, station close to Ringkøbing). A salinity in winter January to February at 3,5-4 psu (reference: surface 1 m, station close to Ringkøbing) does not seem to be negative for Mya Arenaria on a large scale, but too low salinity will negatively affect Mya Arenaria and it is important to have high enough winter salinity to support an average spring salinity Marts to May at minimum 8 psu.

Environmental condition and ecosystem functionality

Salinity

Ringkøbing Fjord, a 300 km² lagoon on the west coast of Jutland, is connected to the North Sea by a sluice at Hvide Sande and with a catchment of 3.470 km^2 of mainly sandy soils.
The salinity varies typically between 10-14 psu in summer and 3-6 psu in winter (Figure 1). The lagoon is generally well mixed both horizontally (Figure 1) and vertically. The sluice operations are decided by a board (Sluseudvalget) and the sluice is operated to have a relatively stable water level aiming for a water level between 0 to 25 cm DVR90 and aiming for a salinity between 12-

14 psu in summer and not below 6 psu throughout the year. The sluice is also operated to minimize inflow in summer in periods with low winds to reduce the risk of stratification and oxygen depletion.
Due to the relatively well-mixed lagoon, st1 is assumed to be acceptable as a proxy for the rest of the lagoon. It is only at st1 that there are long and up-to-date time series of nutrients, chlorophyll, etc.

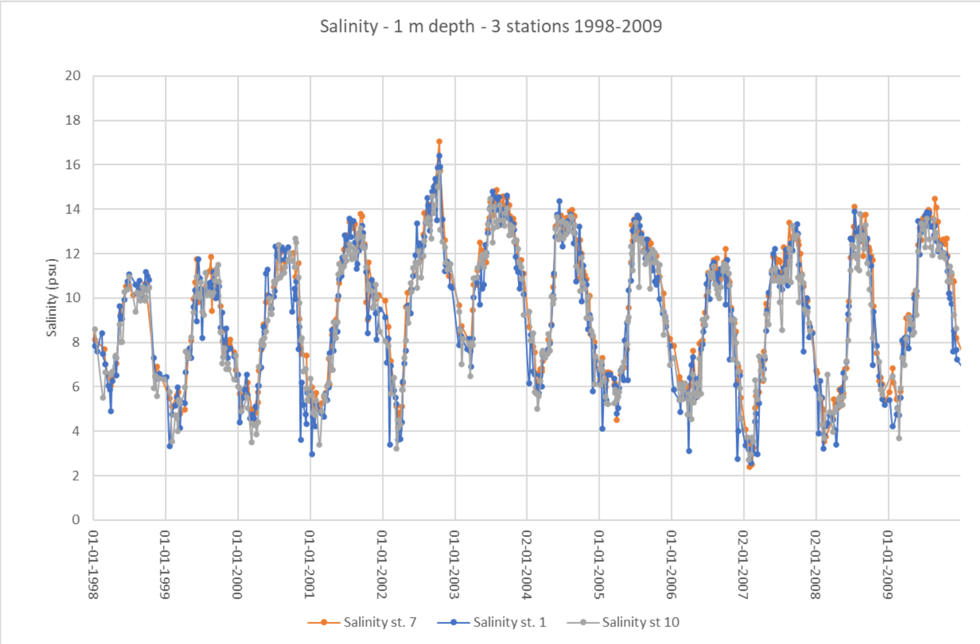

Figure 1. Salinity at 3 different stations from 1998 to 2009. St1. Near to town of Ringkøbing northeast, St7 center of north part of the lagoon, and st10 south of 'klægbanken', approx. 5 km west of the village of Stauning.

The salinity varies from year to year and between seasons due to variations in runoff from the catchment, water level in the North Sea, and how the sluice is operated.
In 1995 it was decided to introduce a higher salinity to improve the water quality in the lagoon (Figure 2). In general, the summer salinity is now between 10-14 psu instead of 8-10 psu and the salinity in spring is now generally 6-8 psu while before 1995 generally 4-6. The winter salinity has not increased and is most years below the goal of a minimum of 6 psu.

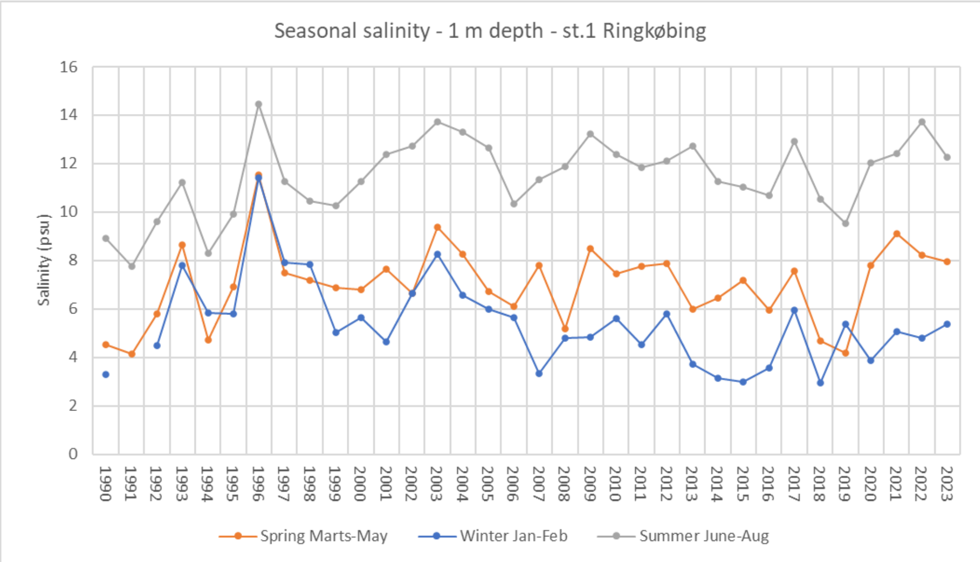

Figure 2. Salinity at st1 (Ringkøbing) in winter (Jan-Feb), spring (Marts-May) and summer (June-Aug). Salinity at approx. 1 m below the surface.

Secchi depth and chlorophyll-a

The ecosystem of the lagoon collapsed in the late 1970's introducing high algae biomasses and low secchi depth values (Figure 3). In the middle of the 1990s, it was decided to obtain a higher salinity and with this decision, the clam Mya Arenaria invaded the lagoon in large numbers with high filtrating rates effectively controlling the algae biomass and therefore also increasing the secchi depth to around 2 m (Published scientifically, ref1).
In 2019 the chlorophyll levels started to increase dramatically again to a summer average of 50 µg/l comparable to the level before the invasion of Mya Arenaria. The hypothesis for the 2019 change is a lack of filtration due to an increased mortality for Mya Arenaria due to a too low salinity in a period around 2018 and 2019. The main difference in salinity for 2018/2019 and other years after 1995 is low salinity in spring and summer while the winter salinity is almost at average (Figure 2). The average summer chlorophyll concentration from 2010-2023 is respectively 11.3 µg/l and 7.7 µg/l including and excluding 2019/2020. When excluding the years with bad filtration (2019/2020) the average level 2010-2023 is below good/moderate value of 8.4 µg/l in the River Basin Management Plan 2021-2027 (ref7).

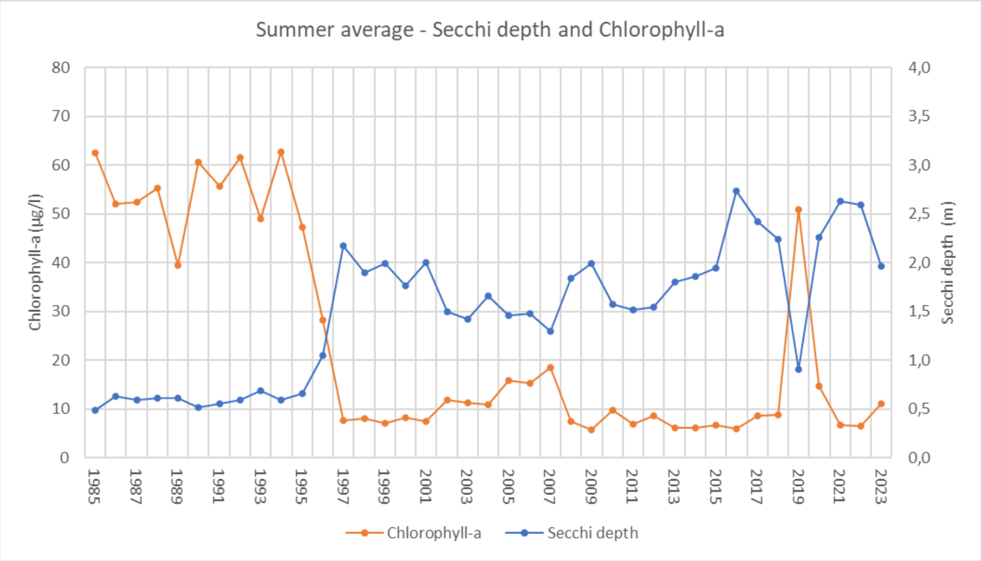

Figure 3. Summer average secchi depth and chlorophyll-a concentration at st1 (Ringkøbing)

The correlation between secchi depth and chlorophyll-a concentration (Figure 4) demonstrates that the filtration from Mya Arenaria is very important for the light conditions in the lagoon and hence the depth limit for the vegetation. The goal in the River Basin Management Plan 2021-2027 for the depth limit is 3.1 m, which suggests that a summer secchi depth of approx. 3.1 m is needed. Using the equation $y=23{,}948x^{-1{,}539}$ with an $R^2=0{,}93$ (Figure 4) suggests that a secchi depth of 3.1 m requires a summer chlorophyll-a concentration of 4.2 µg/l. That is just below half of the current summer 2010-2023 average of 7.7 µg/l when excluding 2019/2020 and half of the target (8.4 µg/l) in the current River Basin Management Plan 2021-2027. In the current ecosystem with Mya Arenaria filtering chlorophyll-a to an average of 7.7 µg/l, it does not seem likely to further increase the summer secchi depth to 3.1 m in the first many years. More vegetation cover in the coming years could, on the other hand, would help to decrease resuspension and therefore could help improve light conditions from 2.5 m to 3.1 m.

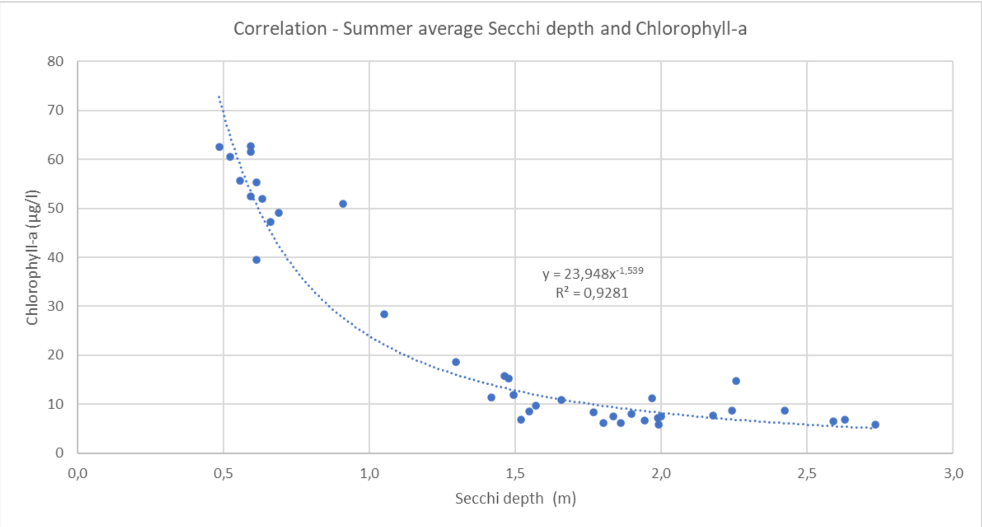

Figure 4. Correlation between summer average (May-Sep) chlorophyll-a and summer average (May-Sep) secchi depth at st1. Ringkøbing. Data 1985-2023.

Secchi depth is not only depending on the chlorophyll-a but also on suspended matter. Ringkøbing Fjord is shallow (average 2 m) and the sediment is resuspended depending on wind. Suspended matter can reach highest levels at 100-250 mg/l Dry Weight (Figure 13). Due to average higher wind speed in winter the wind induced resuspension is higher in winter and lower in summer. This affects the secchi depth and the lowest average monthly values are observed in January and February (0.7 m) and in summer April to September, the highest secchi depth is observed at approximately a monthly average of 1.8 m (Figure 5). This is opposite to open water systems where secchi depth often is affected mainly by chlorophyll.
Due to the nature of wind, the resuspension is highly dynamic with up to a 2 m difference in secchi depth between measurements (Figure 6).

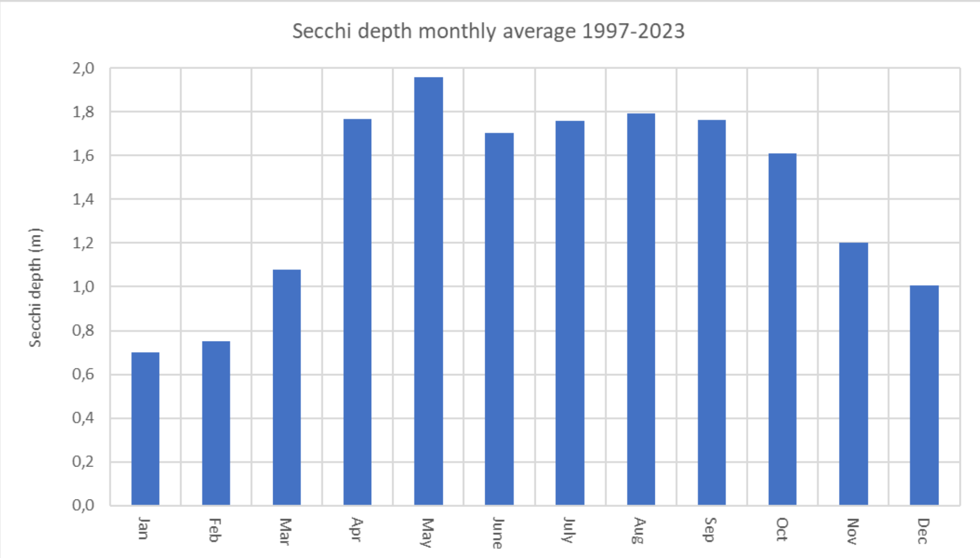

Figure 5. Secchi depth monthly average 1997-2023 at st.1 Ringkøbing.

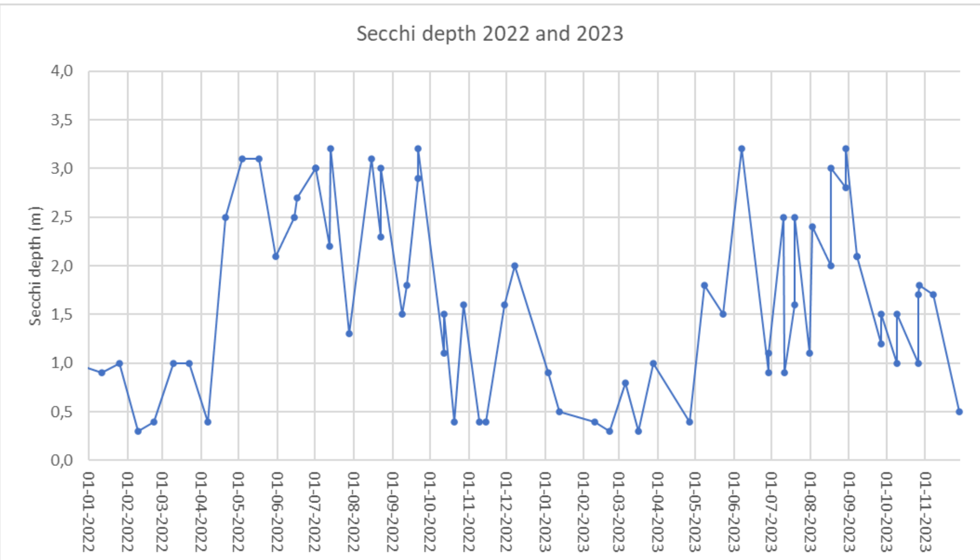

Figure 6. Secchi depth at st1. Ringkøbing in 2022 and 2023. Secchi depth is in some of the measurements limited by bottom depth.

Seagrasses

The wind (due to resuspension) and filtration from Mya Arenaria allows a maximum summer average secchi depth of approx. 2-2.7 m (Figure 4). This maximum summer average is a good prediction for maximum depth limit for sea grasses. Data from monitoring seagrasses close to st.1 Ringkøbing demonstrates exactly that: 10% coverage at 2,5 m and maximum depth limit (1% coverage) at 2.5-3 m (Ref2). The secchi depth at st1 Ringkøbing is correlated with st7 (middle of the Lagoon R^2=0.95) and therefore assumed to be a good proxy for the secchi depth in the lagoon. The good/moderate vegetation depth limit in River Basin Management Plan 2021-2027 is 3.1 m and with the current filtration and resuspension, it seems difficult to fulfill the 3.1 m target at least in the short term. In a longer timescale (decades) it could be possible that suspended matter will decrease and therefore secchi depth will increase.

Nitrate concentration

Nitrate together with phosphorus is main contributors to eutrophication. Nitrate is considered to limit primary production at levels belove 28 µg/l (ref3). The nitrate levels in the lagoon demonstrates the "top-control" from Mya Arenaria on the system: At the same time Mya Arenaria invades in 1995 and chlorophyll reduces from 40-50 µg/l to approx. 8 µg/l the nitrate level increases from below 28 µg/l (redline Figure 7) to 100-160 µg/l in July and August in 1997-1999. Clearly demonstrating that nitrate is not limiting the plankton algae in the system. Due to the top-down control from Mya Arenaria, the eutrophication is instead expressed by macro algae like Ulva and epiphytes (Figure 8). In the first years after the regime shift in 1995/96, an increased problem with Ulva was reported locally. The vegetation was already sparse before the Mya invasion because of bad light conditions but it became even worse due to higher salinity. It took some years for the vegetation to adapt to the higher salinity (ref8) but now the advantage is better light conditions compared to the situation before invasion. Almost 30 years later Ulva seems to have decreased again and the main eutrophication seems to be epiphytes (ref6). The monitoring regarding macroalgae is relatively sparse but at the vegetation monitoring transects epiphytes are reported to cover in average 30% of the vegetation.

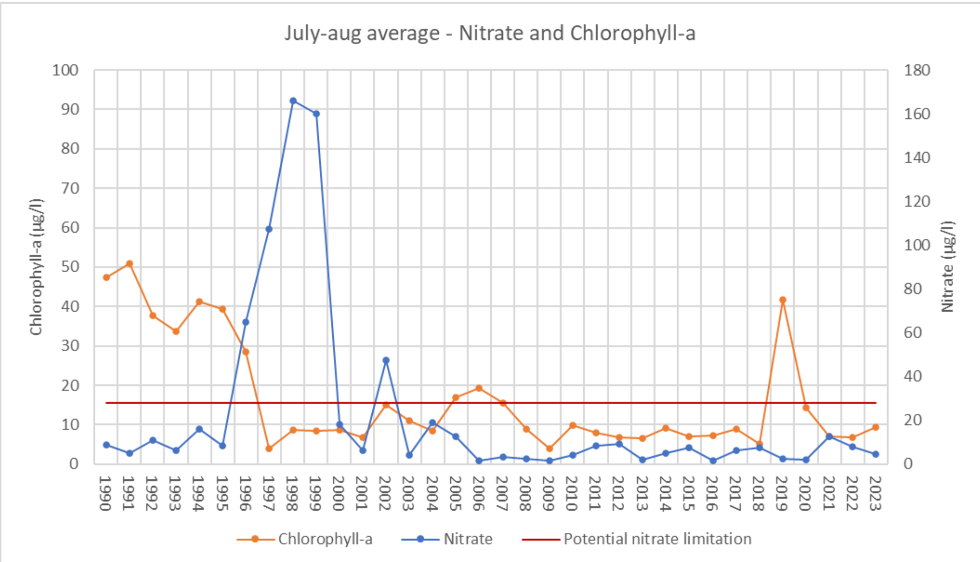

Figure 7. July and August average - Nitrate and Chlorophyll-a. 1990-2023.

Figure 8. Ulva (left) and epiphytes on seagrass (right) Foto: Flemming Gertz.

N-load related to Chlorophyll

N-load is generally correlated to chlorophyll in the Danish River Basin Management Plans since chlorophyll generally have a response to changes in loadings. This is also the case in the latest River Basin Management Plan for Ringkøbing Fjord 2021-2027. But in the case Ringkøbing Fjord the Top-down control from Mya Arenaria disconnect that relation in most years. This is reported by Aarhus University (ref4) with a poor correlation (R^2= 0.08) and also demonstrated by SEGES Innovation (Figure 9 & Figure 10 & Table 1) with no correlation for the period 1998-2019 and 2008-2019. However, there is a period around 2002-2014 (Figure 11) where a correlation can be observed. The best fit (R^2=0,88) is for the period 2007-2014 with May-Aug TN load correlated to May to Sep Chlorophyll-a (Figure 12 & Table 1). The correlations demonstrate that in most years the filtration disconnects the relation between N-loadings and Chlorophyll as a eutrophication response. But the statistical correlations also demonstrate that in some years there can be established a good correlation properly due to a decrease in filtration from Mya Arenaria in that specific period.

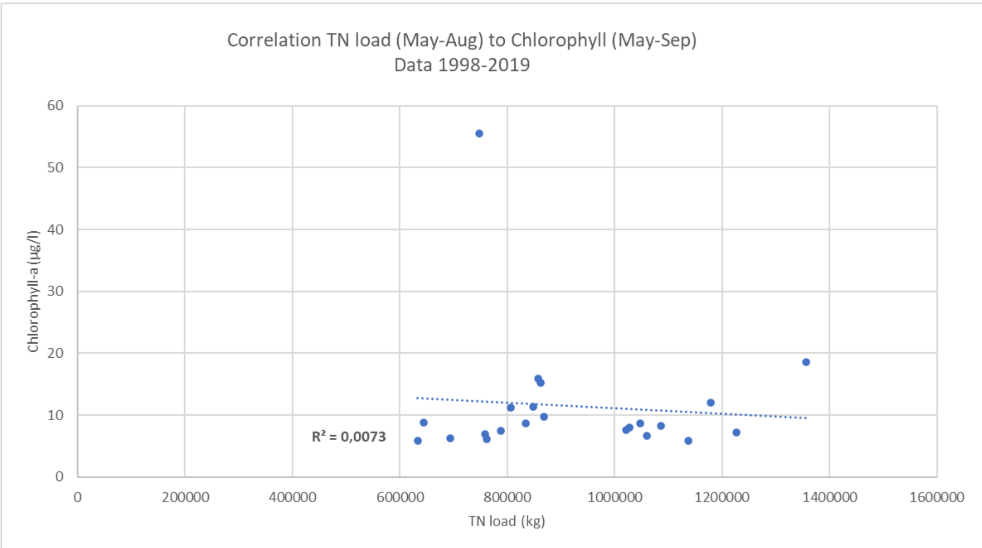

Figure 9. Correlation - Load Total Nitrogen and Chlorophyll-a. st1. Ringkøbing. Data 1998-2019. N-load May-Aug correlated to Summer (May-Sep) chlorophyll.

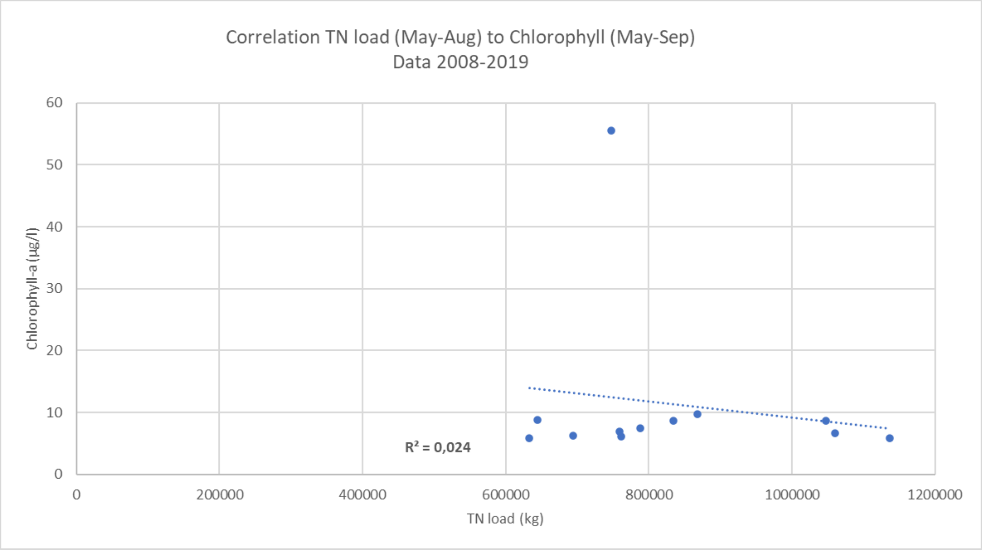

Figure 10. Correlation - Load Total Nitrogen and Chlorophyll-a. st1. Ringkøbing. Data 2008-2019. N-load May-Aug correlated to Summer (May-Sep) chlorophyll.

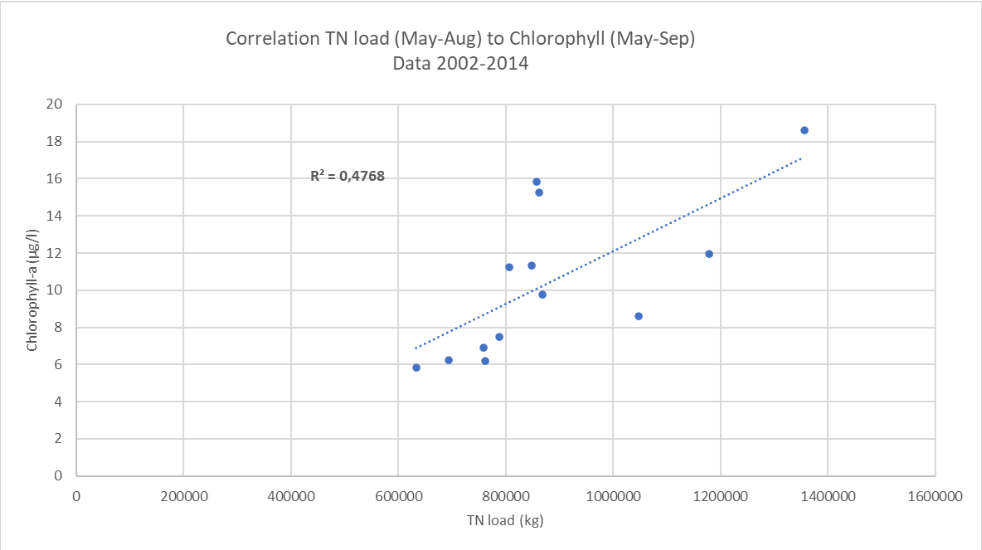

Figure 11. Correlation - Load Total Nitrogen and Chlorophyll-a. st1. Ringkøbing. Data 2002-2014. N-load May-Aug correlated to Summer (May-Sep) chlorophyll.

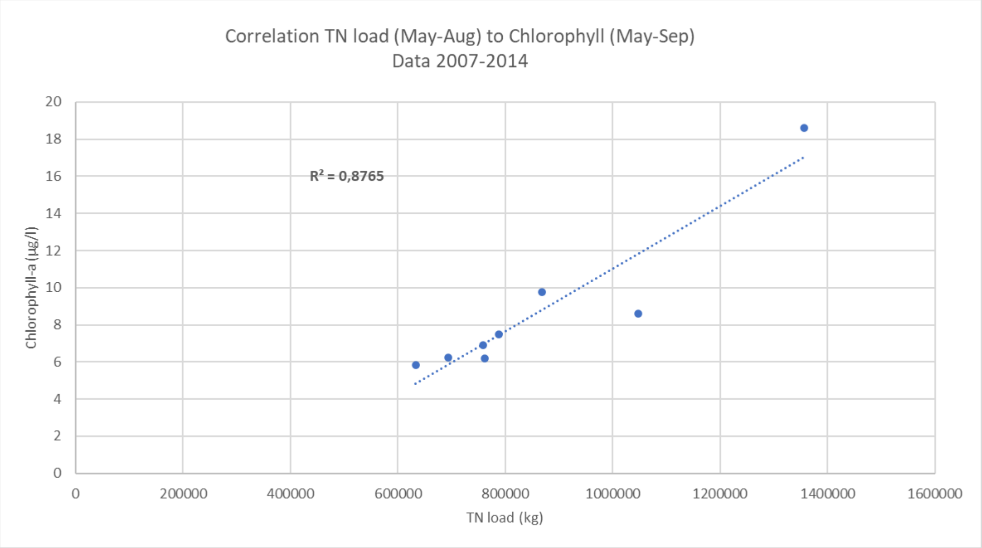

Figure 12. Correlation - Load Total Nitrogen and Chlorophyll-a. st1. Ringkøbing. Data 2007-2014. N-load May-Aug correlated to Summer (May-Sep) chlorophyll.

Correlation TN-load to Chlorophyll-a			
	TN load (May-Aug) Chlorophyll (May-Sep)	TN load (June-Aug) Chlorophyll (June-Aug)	TN load (Jan-Aug) Chlorophyll (May-Sep)
Years	**R^2**	**R^2**	**R^2**
1998-2019	0,01	0,002	0,01
1998-2018	0,09	0,13	0,02
1998-2014	0,18	0,18	0,05
2002-2014	0,48	0,35	0,17
2007-2014	0,88	0,81	0,68
2008-2018	0,001	0,02	0,09
2008-2019	0,02	0,003	0,05

Table 1. Correlations results R^2 for correlation TN-load to Chlorophyll-a for different combinations of years and different combination of month.

N-load related to secchi depth

Aarhus University reports a relation between secchi depth and 3 predictors in a statistic model (ref5) where they find a correlation (R2= 0.81). The 3 predictors are nutrient input, temperature and “TPlim” (a proxy for phosphorus limitation) with “TPlim” as most important. The problem with using TP as a predictor is that TP in the lagoon is related to resuspension (Figure 13). In other words, the secchi depth model is mostly predicting year to year changes is wind conditions and resuspension and not a relation between load and secchi depth. This is in line with the above data – that the secchi depth is depending on chlorophyll controlled by filtration and resuspension controlled by the wind.

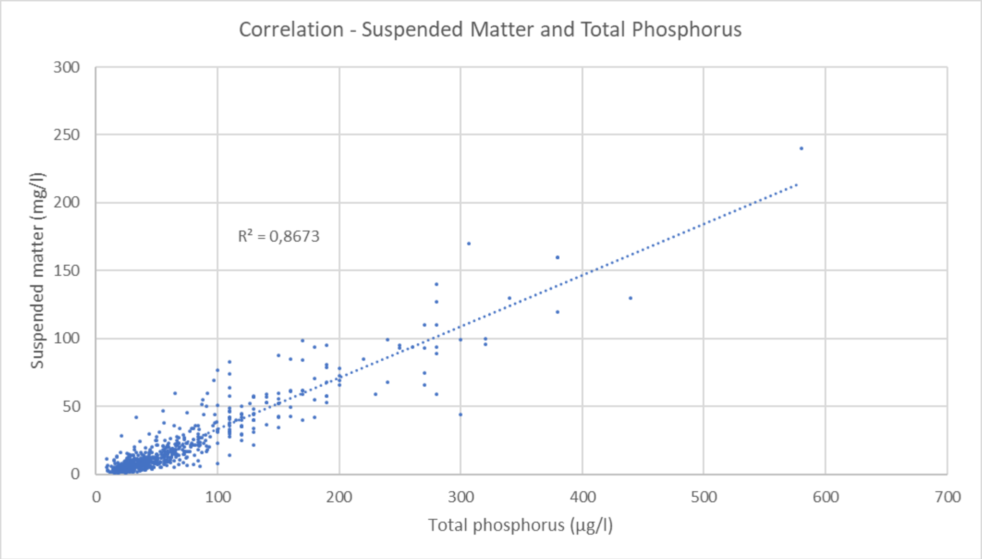

Figure 13. Correlation - Suspended Matter and Total Phosphorus. St. Ringkøbing. Data 1998-2016.

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